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Perspectives on the environmental implications of sustainable hydro-power: comparing countries, problems and approaches

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Abstract Perspectives on the Environmental Implications of Sustainable Hydropower gathers scientific papers from three of the worlds most important hydropower producers to discuss aspects of sustainable hydropower and the means by which it can be studied and achieved. The papers examine the application and use of new technologies and protocols for studying hydropower, adaptive management and the implications and use of long-term data sets for minimizing hydropower impacts on fish populations. The papers include a cross section of biological and hydrological experts. The implicit among country comparisons highlight a number of common hydropower themes, particularly the need to expand from single species studies to include broader consideration of the ecosystem, the importance of maintaining habitat, trait and species diversity and the need for consistently collected long-term data sets.

Keywords Hydropower · Sustainability · Long-term studies · Brazil · Canada · Norway

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Background

The emphasis on green energy has heightened concerns about the environmental implications of the energy we source to run modern societies. In that regard hydropower has typically been seen as an environmentally friendly source of energy, although scientific research has documented a number of negative impacts that would suggest hydropower, as with all energy sources, comes with some environmental costs. Some impacts are obvious e.g., disruption of river continuity (Grill et al., 2019), loss of biodiversity (Lees et al., 2016) and transformation of upstream habitats (Freeman et al., 2001; Garcia et al., 2011), and others are more subtle, e.g., impacts on nutrient flows (Friedl & Wuest, 2002; Seitzinger et al.,

2010) and downstream foodwebs (Kennedy et al., 2016). Hydropower, however, has a long and established record of environmental research and monitoring, much of it driven by construction permitting requirements and project environmental assessments aimed at minimizing project impacts and/or associated with the realization that large impoundments can substantially and negatively alter mercury accumulation dynamics for resident fishes (Pestana et al., 2019). Understanding the environmental consequences of past mistakes and the significance of the future challenges facing hydropower has motivated a large body of research aimed at refining study approaches and better mitigating hydropower impacts. Differences in species assemblages, local geography and the cumulative effects of other stressors on river ecosystems often means study results are not immediately transferable from case to case. Nevertheless, comparisons among nations and systems have the potential to elucidate common concerns, problems and approaches.

Here we bring together a compendium of research on sustainable hydropower from three ostensibly different countries: Brazil, Canada and Norway where hydropower has played an important part in national economic development and the provision of energy to the nation. The nations are among the top hydropower producers in the world and together account for 21.6% of world hydropower production (IEA, 2019). And while seemingly different, Brazil, Canada and Norway display a number of common features: hydropower in Canada and Brazil is dominated by large installations that create large upstream impoundments that impede fish migrations, Canada and Norway share common interests in the effects of hydropower on salmonid fish communities and Norway is increasingly investing in Brazilian hydropower development, bringing with it an approach to sustainable hydropower development that will require adjusting to the local ecology.

Accordingly, in this special issue, our goal was to bring together a series of original studies of hydropower impacts on aquatic ecosystems from nations that often have different approaches (i.e., run-of -the -river in Brazil versus pump storage in Norway) and scales (large in Brazil and Canada versus small in Norway), but common interests in understanding the impacts of hydropower on aquatic ecosystems. To better understand the hydropower history of the countries, the diversity of their approaches to hydropower development and the legal and social frameworks underlying the emphasis placed on the sustainable development of hydropower, Alfredsen et al. (2021) review the development and key legislative history for hydropower in each country. We then present a diverse series of scientific studies that have examined the ecological impacts and lesson learned from hydropower development. It is hoped that the collection will contribute to highlighting both the diversity and similarity of problems encountered across the globe with the study and achievement of sustainable hydropower worldwide.

Lessons from Brazil

In Brazil, a widespread environmental issue associated with hydropower facilities is their impacts on migratory species as a result of reduced connectivity and/or the negative interaction effect of dams on fish. For example, dam tailraces can attract and congregate fish in the artificial flow field created by dam tailraces, which can lead to high mortality events during turbine start/stop procedures, particularly if fish have entered the turbine draft tubes. To investigate how turbine operations influenced the flow field downstream of a dam, Mendes et al. (2021) used calibrated numerical two- and three-dimensional hydraulic models to assess flows in the dam tailrace and a 3-km downstream river reach. Model outputs were evaluated taking into consideration the swimming capacities of mature individuals from three common migratory fish species: *Prochilodus costatus* (Valenciennes, 1850), *Pimelodus maculatus* (Lacepède, 1803) and *Leporinus reinhardti* (Lutken, 1874). The models revealed that flows in the tailrace exhibited higher strain, but lower velocity, and were more evenly distributed than those in the downstream section. Downstream hydraulic conditions conducive to creating migratory corridors for the study species declined with increasing turbine discharge, but were still present even at the highest evaluated turbine discharges. Although migratory species were still potentially able to reach the tailrace under high turbine discharges, use of elevated discharges nonetheless has the potential to reduce the numbers of fish entering the tailrace and at risk of mortality. Improved understanding of how fish interact with downstream hydraulic flows, therefore, has the potential to minimize dam operation impacts and improve the sustainability of standard turbine start-up and dewatering procedures.

In situations where fish inevitably enter turbine draft tubes, reducing mortality during start-up and dewatering may be achieved by scheduling the procedures at times when the abundance of fish in the draft tube is low. Braga et al. (2021) assessed the use of dual-frequency identification sonar (DIDSON) to estimate the number of fish present in turbine draft tubes using three different approaches: counting all fish in a frame; counting the number of intersections in the DIDSON grid with fish; and estimating the percentage of the frame including fish. Total counts of fish in DIDSON images of draft tubes provided good estimates of abundance when there were no dense aggregations of fish and when bubble curtains and images exhibited good contrast between fish and turbine tube floor (Braga et al., 2021).

Although fishways have been widely deployed to enable the passage of migratory fishes through hydropower dam, their need and/or efficiency in many situations have been questioned for Neotropical fishes (Pelicice & Agostinho, 2008; Lira et al., 2017). Hahn et al. (2021) assessed the efficiency of a fishway for enabling passage of migratory goliath catfish through a large dam (about 2.5-km wide) recently constructed in the Amazon basin. Individuals from three species of goliath catfish (*Brachyplatystoma rousseauxii* (Castelnau, 1855), *B. platynemum* (Boulenger, 1898) *and B. vaillantii* (Valenciennes, 1840)) were tagged with radio transmitters, released 2000 m downstream of the dam and their movements at the vicinity of the dam were monitored for nearly four years. Only 15% of tagged individuals were detected near the dam, preferring to spend their time near spillways and turbine outlets. Active release of radio-tagged fish in front of and in the lower and middle sections of the fishway indicated that although many were subsequently detected in the fishway, the majority (50–78%) were later detected downstream and only a low percentage (12%) were determined to have passed through the fishway into the reservoir. The low attraction and passage efficiency of the fishway suggests current designs are ineffective, largely because they fail to account for dam hydraulic attraction effects and the behavioural cues they provide. As suggested above (Braga et al., 2021; Mendes et al., 2021), improved understanding of the interactions between river hydrology downstream of dams and fish will be key to ensuring fish encounter and react to dams in ways that will minimally disrupt their ecology and life-history.

One potential issue with the use of fishways as a management tool for Neotropical species is that, by enabling fish to reach spawning grounds upstream of reservoirs (even though suitable spawning grounds may be available downstream of dams), their eggs and larvae may suffer high mortality as they drift downstream through the dam created lentic environment and/or move through turbines or spillway intakes (Pelicice et al., 2015; Boys et al., 2016). Brambilla et al. (2021) studied the downstream dispersal of fish eggs and larvae through reservoirs created by small hydropower facilities to determine which factors influence their drift and whether downstream passage through fishways can occur. The authors regularly sampled larvae and eggs from the riverine, transition and lentic zones of two small reservoirs as well as in the fishways associated with the dams forming the reservoirs. The findings revealed that eggs and larvae are able to drift through the reservoirs and reach the dams, with their density at different sites and sampling periods varying with rainfall and turbidity. The authors also determined that eggs and larvae can pass downstream through the fish ladders. Although larval density in fishways exhibited a positive relationship with larval density in the lentic zone, the density of larvae in the fishways was only 14.6% to 65% of the larval density in the lentic zone. Furthermore, larval density in the fishways declined with increases in turbine and spillway discharge. Collectively, these findings indicate that despite successfully drifting though small reservoirs, the majority of eggs and larvae might pass downstream through turbines and spillways, which may result in high levels of mortality. Similarly, Vasconcelos et al. (2021) examined the impacts of hydropower facilities on fish eggs and larvae and their downstream dispersal through the reservoir to determine if dams act as significant barriers. While short reservoir retention times did not appear to have drastic effects on either life stage, results where not uniform across all considered taxonomic groups of fish, with adaptive Perciformes and Clupeiformes species with pelagic eggs being least affected. For other groups of fishes, larval densities decreased as a function of downstream distance, either as a result of mortality or displacement of individuals to unsampled habitats.

While most of the studies conducted in Brazil and presented in this special issue focused on addressing specific and localized technical questions related to fish and hydropower interactions, Pelicice et al. (2021) investigated hydropower impacts by assessing large-scale patterns of fish species richness and their functional traits in a meta-analysis of large Brazilian reservoirs. Using data from 378 species and 79 reservoirs, hydropower reservoirs were associated with high rates of fish species turnover within and across major drainage basins, likely as a result of reservoir size and age and the effect of varying biogeographic filters on the evolutionary history of species in each river basin. Contrary to expectations reservoirs did not appear to homogenize fish communities by selecting for similar functional traits, with functional trait turnover within and across basins also being high. Functional trait turnover was also strongly correlated to species turnover, leading the authors to suggest that functional trait diversity is driven by species composition.

Lessons from Canada

Much of Canada's hydroelectric potential has been developed and used for a considerable period of time and, as a result, Canada has accumulated a wealth of operational experience with the study and mitigation of environmental impacts of hydropower. Scale, however, continues to be a challenge as the country moves from the traditional large, bulk storage facilities that have damned large northern Canadian rivers (e.g., James Bay, Peace River) to smaller more flexible production capable of backstopping other renewal energy sources to ensure the continuous availability of generation capacity. While many of the lessons learned from years of operational experience can inform future integrative management of fisheries resources affected by hydropower (Bett et al., 2021), emerging technologies designed to optimize smaller scale generation of hydropower in rivers demand use of novel, purpose designed experimental studies for understanding environmental impacts. Using balloon-tag and telemetry technologies Tuononen et al. (2021) were able to expand understanding of the impacts of very low head turbines on a variety of fish species and corroborate earlier studies suggesting very low head generation turbines have minimal impacts on the mortality (immediate and delayed) and morbidity of entrained fish. Although issues with entrainment impacts on population abundances and loss of connectivity remain to be solved, studies such as that completed by Tuononen et al. (2021) point to ways in which technology design may avert some of the traditional environmental impacts of hydropower generation.

Technological change, however, can create as well as reduce environmental impacts. Increased emphasis on renewable energy sources (e.g., wind, solar) comes with the need to have backstop generation capacity able to provide power when environmental conditions preclude the use of renewable sources. Hydropower, with its ability to store water and quickly increase or decrease production via flow control (i.e., hydropeaking) has a natural role to play in the development of a larger portfolio of renewable energy sources. Hydropeaking, however, has environmental costs and is generally considered to be one of the more ecologically harmful modes of hydropower operation given the documented downstream effects repeated surges and riverbed drying can have on resident biota (Smokorowski, 2021). While studies to date generally suggest hydropeaking is harmful, the results are contradictory and appear to vary in ways that depend on river morphology and which resident species are being described (Smokorowski, 2021). The design of improved operational regimes and the incorporation of newer generation technologies that will better conserve and protect fish and fish habitat from the consequences of hydropeaking will demand co-ordinated planning and study among all entities, producers, regulators and stakeholders, and remains a challenge for hydropower research (Smokorowski, 2021).

The many years of operational experience with large Canadian hydropower projects have also generated a wealth of information as result of pre- and post-construction assessment and monitoring (Bradford, 2021). In western Canada the creation of environmentally sustainable hydropower operations has focused on ensuring appropriate fish passage and flow availability to facilitate passage. Primary emphasis on target salmonid species has tended to mean regulations and mitigative actions are directed at ensuring the sustainability of only a subset of resident species, with the result that there can be unintended environmental consequences, including reduction in the diversity of fish habitats (Bradford, 2021). Thus it is possible both to achieve regulatory targets for ensuring the sustainability of key fish populations and, at the same time, fundamentally alter river ecosystem processes.

Better understanding of the accuracy of pre-construction predictions for fish and fish habitat has led to an expansion in the tools and methods used to draw inferences about likely dam and reservoir effects, with genetic, telemetry, and the stable isotopic studies now routinely supplementing traditional survey approaches. Combined these approaches have highlighted the role of tributary streams as key spawning, nursery, and feeding habitats for resident fishes (Bradford, 2021). Understanding ecological flow requirements has also become a key tool for understanding and regulating the impacts of hydropower production (Katopodis, 2021). And while there is great potential for the use of ecological flow methods, they are data hungry and present multi-jurisdictional, legislative, climatic and geographic challenges. Such challenges can be offset by innovative data collection technologies (e.g., remote sensing) and analytical methods, but these in turn will need to account for possible climate change effects (Katopodis, 2021). Critical for the determination of environmental flows will be an emphasis on longterm data collection and co-ordination among industry, regulators and academic study to ensure the approaches used for setting environmental flows meet the life-history and connectivity requirements of resident fauna and flora and any associated aquatic habitat restoration aims (Katopodis, 2021).

Integrative research aimed at improved understanding of hydropower is a theme echoed in much of the research on hydropower and is looked at as the best means of developing effective solutions for ensuring the environmental sustainability of hydropower (Bradford, 2021; Katopodis, 2021; Bett et al., 2021). Bett et al. (2021) review the longterm research efforts on one hydropower impacted system in British Columbia, Canada, to show how combined use off biological (behavioural, physiological and molecular approaches) and hydraulic monitoring were combined to develop operational guidelines for hydropower aimed at ensuring the sustainability of affected migratory fishes. Over time more holistic approaches to predicting and understanding dam impacts have developed in Canada, but depend on the co-operative commitment of multi-party interests (industry, government, academia) and long-term, sustained levels of research and data collection (Bett et al., 2021; Bradford, 2021; Katopodis, 2021; Smokorowski, 2021). Nevertheless, hydropower effect prediction for fish populations inhabiting large rivers remains difficult because of their migratory nature, diverse life-histories and habitat use requirements, and reliance on complex food webs (Bradford, 2021). Because predictions will remain uncertain, and in the future will need to account for the large-scale environmental changes imposed by climate change, hydropower effects assessment practice will need to remain adaptive, flexible and will need to continue to rely on formalized expert-driven assessment processes (Bradford, 2021).

Lessons from Norway

In Norway, environmental studies of hydropower have mostly focused on mitigating negative effects on Atlantic salmon (*Salmo salar* (Linneaus, 1758)) populations, since approximately one third (144 of 448 populations) of all rivers in Norway with this socio-economic important species are regulated for hydropower (Anon., 2020). A milestone in the management of regulated salmon rivers was the development of the concept of “environmental design for hydropower” in 2013, which is described in a practical handbook used by consultancies, managers, and hydropower companies today (Forseth & Harby, 2014). Although ongoing research aims to expand the environmental design concept in regulated salmon rivers by including other species, ecosystem components and user interests (e.g., Skår & Köhler, 2019; Helland et al., 2019), most of the Norwegian research continues to focus on salmonid fishes in rivers.

Habitat improvements, such as spawning gravel augmentations for salmonids, are a common mitigation measures in regulated rivers in many countries. Thus it is important to evaluate the efficiency and perform cost–benefit analyses of the practices. Pulg et al. (2021) monitored the long-term effects of spawning gravel augmentations in three rivers in western Norway and concluded that the measures had long life span (up to 18 years) at relatively low cots (1.05 € m^2-$year^{-1}$), and significantly increased Atlantic salmon and brown trout (*S. trutta* (Linnaeus, 1758)) reproduction. The three Norwegian rivers presented in the paper covered a range of average discharges and design floods, and provided information on the lifespan of the gravel adjustments under different flow conditions. The success of such measures, however, depends on the river flow regime and events such as large floods or input of fine sediments, implying the necessity of adapting the approach for use in the other countries where river geomorphologies and species may vary,

A prerequisite for identifying relevant mitigation measures in regulated rivers is to have knowledge about the environmental requirements of key species and some information about how the hydropower operation affects the habitat. Detailed habitat mapping using hydraulic models is often very time consuming, but in recent years the development of remote sensing technology has opened new possibilities for detailed terrain models and high resolution bathymetric data. Sundt et al. (2021) used available green LIDAR data, which can penetrate water, together with areal images to investigate mesoscale habitat characteristics in two large-scale Norwegian rivers based on high resolution hydraulic modelling. Spatial and hydraulic heterogeneity were found to explain European grayling (*Thymallus thymallus* (Linnaeus, 1758)) occurrence during the spawning period, a fact underlining the importance of maintaining variability in river habitats.

The harmful effects on fish from the supersaturation of total dissolved gas in the water downstream of hydropower plants have received relatively little attention in Norway compared with North America, even though Norwegian production systems with multiple intakes can cause significant air entrainment. The controlled field study by Stenberg et al. (2021), however, indicates that Atlantic salmon may be more vulnerable to supersaturation than studied Pacific salmonids, with differences also being evident among life-history types. Landlocked Atlantic salmon were more susceptible to gas bubble disease and mortality than anadromous conspecifics, although it was not clear if the differences related to greater sensitivity to supersaturation in non-anadromous populations or other unmeasured differences between study sites and populations. Findings, however, point to the need to better document and understand the causes of any species-or life- history-specific tolerance levels, before creating guidelines setting the maximum total dissolved gas levels permitted for adequate protection of aquatic organisms.

In Norway, concerns have also been raised about the proliferation of the macrophyte *Juncus bulbosus* (L.) after the development of hydropower. This submerged vegetation is considered a nuisance for humans in many rivers, and measures have been tested in several regulated rivers to remove the vegetation. However, Velle et al. (2021) concluded that *J. bulbosus* is not limiting for salmonids and benthic macroinvertebrates, with higher densities of juvenile fish and higher invertebrate densities, weights and richness occurring in areas with J. *bulbosus* than in areas with clean gravels. The findings underline the importance of studying ecosystem effects rather than individual species, and the need to distinguish nuisance to humans from effects on the ecosystem as a whole.

As in Canada and Brazil, fish migration continues to be an important topic for hydropower research in Norway. While solutions for the upstream migration of Atlantic salmon are well developed, downstream migration and measures to prevent fatal turbine passage remain as major challenges for salmonids and other species. Haraldstad et al. (2021) expanded our understanding of how hydropower can exert selective pressures on fish populations, with migration route choice having significant impacts on survival probability (turbine vs bypass passage), and act in concert with natural size-related predation selection to yield increased phenotypic and genetic variation. Thus while the hydropower turbine passage favours smaller sized fish, the same individuals are more exposed to predation from Northern pike (*Esox lucius* (Linnaeus, 1758)). Such opposite selection gradient effects will combine to cause disruptive selection that results in extreme trait values increasing in frequency. Thus, the choice of mitigation measures for hydropower has the potential to play an important role in maintaining the genetic variation in populations necessary to ensuring their long-term survival.

Synopsis

Considered together, the papers in this issue point to a series of important conclusions regarding the sustainability of hydropower and the ways in which it can be made and maintained as environmentally friendly as possible. Technology and technological change emerging from environmental studies have important roles to play, in the context of providing researchers with new tools to understand the nuances of fish ecology, such as downstream larval dispersal (Brambilla et al., 2021), and fish interactions with hydropower facilities (Hahn et al., 2021). New hydropower engineering technologies will be similarly important for understanding how hydropower operational regimes may be adjusted to account for fish behaviour in ways that will reduce overall mortality (Smokorowski, 2021; Stenberg et al., 2021; Tuononen, et al., 2021). Thus digitalization and new methods for field data collections have improved applied environmental studies and pointed to the many subtleties of fish interactions with dams (Braga et al., 2021; Hahn et al., 2021; Sundt et al., 2021). High resolution data collection systems will undoubtedly come to be more commonly deployed and will facilitate the development of detailed models (Katopodis, 2021; Mendes et al., 2021) able to better and more quickly identify trade-offs within hydropower production systems that will facilitate improving their overall environmental sustainability.

Studies have also underlined the importance of expanding from a single, often highly valued, species focus to a broader ecosystem perspective that highlights the importance of habitat, trait and species diversity (Bradford, 2021; Pelicice et al., 2021; Velle, 2021). To accomplish that, studies will increasingly need to move from evaluating the immediate present-day impacts of hydropower production, to studying effects over the longer term on populations and communities (Bradford, 2021), in part because of the lag effects associated with many of the direct effects of hydropower development. Only with the availability of good multiple endpoint data can we hope to ensure the development of appropriate adaptive and integrative resource management strategies that include effective, cost-efficient mitigation measures (Bett et al., 2021; Haraldstad et al., 2021; Pulg et al., 2021). Thus long-term data sets will become increasingly important for the sustainable management and mitigation of hydropower effects, especially in multi-species systems (Bett et al., 2021; Katopodis, 2021). And, from an ecosystem perspective, it has become increasingly clear that one has to be careful about over regulation of hydropower systems for the apparent benefit of a single species (Bradford, 2021).

Collectively, the papers presented in this issue have built on a long history of hydropower related research in Brazil, Canada and Norway and have underlined the increased knowledge we have gained with respect to the development and operation of hydropower that has minimal environmental effects. And while challenges remain, judicious use of technical innovation and long-term data sets have the potential to generate the information and understanding required to develop adaptive management and mitigative solutions for hydropower impacts across the globe, particularly given the diversity of scientific expertise and experience being developed in nations like Brazil, Canada and Norway.

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